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Operational planning optimization of steam power plants considering equipment failure in petrochemical complex

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HIGHLIGHTS

- ▶ We develop a systematic programming methodology to address equipment failure.
- ▶ We classify different operation conditions into real periods and virtual periods.
- ▶ The formulated MILP models guarantee cost reduction and enough operation safety.
- ▶ The consideration of reserving operation redundancy is effective.

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ABSTRACT

One or more interconnected steam power plants (SPPs) are constructed in a petrochemical complex to supply utility energy to the process. To avoid large economic penalties or process shutdowns, these SPPs should be flexible and reliable enough to meet the process energy requirement under varying conditions. Unexpected utility equipment failure is inevitable and difficult to be predicted. Most of the conventional methods are based on the assumption that SPPs do not experience any kind of equipment failure. Unfortunately, a process shutdown cannot be avoided when equipment fails unexpectedly. In this paper, a systematic methodology is presented to minimize the total cost under normal conditions while reserving enough flexibility and safety for unexpected equipment failure conditions. The proposed method transforms the different conditions into real periods to indicate normal scenarios and virtual periods to indicate unexpected equipment failure scenarios. The optimization strategy incorporating various operation redundancy scheduling, the transition constraints from equipment failure conditions to normal conditions, and the boiler load increase behavior modeling are presented to save cost and guarantee operation safety. A detailed industrial case study shows that the proposed systematic methodology is effective and practical in coping with equipment failure conditions with only few additional cost penalties.

1. Introduction

In recent years, energy shortage and environmental pollution problems have become the focus of the world's attention. The industrial sector accounts for one-third of the global energy consumption. Although the processes used in the industrial sector are highly diverse, their common feature is their reliance on fossil fuels as their primary source of energy. The reliance on fossil fuels as the primary source of energy has a huge negative impact on the environment and ecosystem of our planet. Industrialization in developing nations and especially that in China will drastically increase the global energy demand, posing an adverse impact on the environment. Improving energy efficiency and reducing pollutant emission have been the most important issues in recent years.

Petrochemical production is an energy-intensive industry. A petrochemical complex usually contains one or more interconnected steam power plants (SPPs) to provide utility energy to different processes. To avoid large economic penalties or system operation failure, these SPPs should be flexible and reliable enough to meet the process energy requirement under various conditions (e.g., varying prices, demands, and equipment availability). Therefore, the design and operation performance of SPP has a significant influence on the safe, steady, and economic operation of the process corporation.

Significant efforts and contributions have been made to address the optimization of industrial SPP through various characteristics. Papoulias and Grossmann [1] presented a general mixed-integer

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Nomenclature

Sets

BN	{*bn*|boilers}
D	{*d*|pollutants}
I	{*i*|steam power plants}
J	{*j*|steam power plants}
K	{*k*|fuels}
LN	{*tn*|letdown valves}
N	{*n*|all units}
R	{*r*|steam levels}
ST	{*st*|virtual operation periods}
STBN	{*stbn*|boiler failure circumstances}
STTN	{*sttn*|turbine failure circumstances}
T	{*t*|real operation periods}
TN	{*tn*|turbines}
Z	{*z*|turbine reheat extraction outlet}

Parameters

a, b	user-specific coefficients obtained from performance curves or regressed from operating data for a specific type of boiler such as PCFB, GFB, CFBB, and WCFB
C	cost of fuel, imported electricity, and emission charge, ¥/t or ¥/MW
CA	material consumption cost for unit pollutant reduction; ¥/t
HR	annual operation time, h
O	average allocated equipment maintenance and depreciation cost; ¥/t
OA	average allocated operation cost for unit pollutant reduction; ¥/t
P	time duration of period, h
q	low heat value of fuel, kJ/kg
u, v, ρ, σ	user-specific model coefficients of turbine obtained from performance curves
θ	period time length percentage
ω	weight of the satisfaction level of each criterion

Variables

E	power electricity load, MW
F	fuel flow rate, t/h
G	amount of pollutant emission, t/h
GA	reduced amount of pollutant, t/h
M	flow rate of steam or water, t/h
ORD	element order of a set
T	adjusting time duration, minute
Y	binary variable denoting the equipment states

Superscripts

dem	steam or electricity demand
e	emergency circumstances
f	fuel
gen	generation
impE	imported electricity
in	inlet
L	minimum value
out	controlled extraction and condense steam
reg	uncontrolled extraction
s	steam
U	maximum value

linear programming (MILP) framework for SPP optimization, and their work was extended to multi-period MILP models by Iyer and Grossmann [2,3]. Kalitventzeff [4] developed mixed-integer nonlinear programming (MINLP) models for the management planning of utility networks. Papalexandri et al. [5] performed a flexible operational planning optimization that accounts for the uncertainties of utility demand and turbine efficiency. El-Halwagi et al. [6] presented a systematic procedure for the simultaneous utilization of combustible wastes, thermal management of the process, and cogeneration of power. A shortcut method of extractable power calculation was developed to target the power cogeneration potential between classified steam headers. Wang et al. [7] presented several candidates of cogeneration cycles to recover waste heat from the preheater exhaust and clinker cooler exhaust gases in a cement plant. Exergy analysis and parameter optimization were performed for each cogeneration system to achieve the maximum exergy efficiency. Sayyaadi [8] performed multi-objective optimization to design a CGAM cogeneration system while simultaneously considering the exergetic, economic, and environmental aspects. The thermoenvironomic objective function was formed by integrating the thermoeconomic objective and the environment objective. A multi-objective evolutionary search algorithm was developed to find the set of Pareto optimal solutions with respect to the thermoenvironomic objective function and exergy efficiency objective function. Agha et al. [9] proposed an integrated approach that couples the scheduling of the manufacturing unit with operational planning of the utility system in a batch plant. Their demonstration results indicate that the proposed integrated approach leads to a significant reduction in energy costs and a decrease in the emission of harmful gases compared with the results of the traditional sequential approach. Salta et al. [10] established a methodology for the planning optimization of industrial combined heat and power plant. A primary energy savings indicator and a total primary energy savings indicator were developed to evaluate the energy saving of CHP under different power to heat ratios. The developed methodology enables energy planners to identify the optimum CHP capacity according to the specific features of an industrial sub-sector or unit. Carpaneto [11,12] developed a comprehensive approach based on multiple time frames for cogeneration planning in the presence of different scales of uncertainty. Cristóbal et al. [13] developed a rigorous bi-criteria MINLP model to select the best retrofitting options, including CO_2 capture technologies, in a coal-fired power plant. Their numerical results indicate that carbon capture with monoethanolamine performs better with soft environmental limits, and oxy-fuel combustion is the preferred choice when more stringent environmental limitations are considered. Tina and Passarello [14] performed the optimization of short-term hourly scheduling (1 week ahead) of cogeneration plants inside large industrial sites to find the operation points that maximize the profits from the sale of heat and electricity. The application of the optimization method ensures that the plant meets the cogeneration indices that are imposed by the current Italian law and enables the plant to increase its yearly profit by approximately 6% in comparison with the application of a typical CHP management system based on a prefixed distribution of heat demand for each unit.

The aforementioned optimizations for single SPP or multiple interconnected SPPs towards distinct goals have been accepted both in academic research and industrial application [15–19]. However, the optimization results based on these methods are achieved under the assumption that the SPP and the processes do not experience any kind of equipment failure during the operation horizon. Therefore, a process shutdown is unavoidable even when a small equipment shuts down unexpectedly when applying

the schemes achieved using the conventional operation optimization method.

Major equipment shutdowns in SPP, which drastically decreases steam production, occur frequently [20]. Many studies on preventive maintenance optimization methods have been proposed to prevent equipment failure. Vassiliadis and Pistikopoulos [21] proposed an MINLP model to search for optimal preventive maintenance policies under parametric uncertainty to maximize system effectiveness. Ogaji et al. [22] described the recent developments in engine diagnostics to improve power plant availability using advanced techniques such as artificial neural network- and genetic algorithm-based techniques. Kim et al. [23] proposed a preventive optimization framework to obtain the optimal operation that can prevent plant shutdown in the case of unexpected equipment failure in a utility plant. Emergency handling constraints to avoid plant shutdown by performing predetermined emergency response actions are incorporated into the conventional optimization model. Eti et al. [24] introduced a proper integration method of reliability, availability, maintainability and supportability as well as risk analysis in each maintenance process in the Afam thermal power station to reduce the frequency of failure and maintenance costs. Aguilar et al. [25] developed a systematic methodology to address the design and operation of flexible utility plants by incorporating reliability and availability considerations. Preventive maintenance approaches provide a quantitative method for reducing the frequency of equipment failure or for minimizing the effect of equipment failure. However, predicting the exact rate of equipment failure at a specific operating period is impossible because it is not only a function of time but also of temperature, pressure, and the number of start-ups and shutdowns.

As discussed above, the solutions based on the conventional planning optimization model usually feature optimal in economic objective or thermodynamic efficiency but fail to provide enough safety and flexibility for the process operation. Process shutdowns due to utility energy shortage triggered by unexpected equipment failure cannot be avoided. A process shutdown usually results in significant losses or damages. Although some efforts and contributions have addressed availability or reliability for SPPs or cogeneration plants, they are only focused on single equipment or simple cycles [26]. Industrial SPPs are more complex because they involve various types of equipment, multiple steam levels, multiple interplant pipe connections, and many kinds of utility energy users. An effective and practical measure is to reserve load redundancy during the design and operation of such SPPs to reduce the effects of unexpected equipment failure [25]. However, the SPP cannot be immediately changed from one operation condition to another (e.g., increasing the operating load of the boiler, decreasing the steam consumption of turbine, and importing power from a local power grid) to cope with emergency circumstances, although enough redundancy is scheduled. Moreover, the frequency and time duration of equipment failure are relatively small compared with those under normal conditions. Enabling the SPPs to operate under equipment failure mode all the time is unnecessary. Therefore, the operation scenarios must be classified and represented reasonably to reduce the total cost under normal scenarios while reserving enough redundancy to cope with equipment failure scenarios within a few minutes of process buffer time. In the present study, a novel modeling framework is developed to address the operational optimization considering unexpected utility equipment failure. The operation scenarios are classified into real and virtual periods. The operational optimization models are formulated for both real and virtual periods. The transition constraints and maximum power importation penalty are incorporated into the conventional optimization framework. Moreover, an industrial case is elaborated to validate the developed strategy and model.

This paper is organized into six parts, including this Section 1. Section 2 compares the different operation schemes with and without the consideration of equipment failure through a small example. The optimization strategy is introduced in this section. Section 3 describes the classification of time scenarios to represent different operation conditions. The detailed MILP models are presented in Section 4. Section 5 shows a case study to testify the effectiveness of the proposed methodology. Conclusions and future extensions of this work are given in Section 6.

2. Problem description

The boiler and the turbine are the two main equipment in SPPs, and their availability greatly affects the safe and economic operation of processes. The utility energy supply decreases drastically when one or more equipment fail. The utility energy shortage may threaten the safety of the process operation. The current study recommends the operation strategy of reserving operation redundancy to cope with emergency situations such as unexpected utility equipment failure. However, the cold start of the main equipment (e.g., boiler and turbine) in SPPs usually takes several hours. Moreover, the steam production of an operating boiler cannot be immediately increased to the desired value because of mechanical limitations. Although enough redundancy (backup equipment) has been considered in the design stage, starting up the cold backup equipment to cope with emergency circumstances within an acceptable time is impossible. Process shutdowns due to the shortage of utility energy triggered by unexpected equipment failure are unavoidable if the emergency circumstances are not handled exactly in the optimization routines. Consequently, significant losses or damages are unavoidable. Therefore, planning or scheduling operation redundancy can be difficult because of the multiple operation scenarios (e.g., normal conditions and emergency conditions) and the complex transition behavior of SPP from normal operation to emergency operation. If the sudden utility energy shortage of emergency conditions could be supplemented within a certain amount of time, which is called the process buffer time (usually a few minutes) in Ref. [23], then process shutdowns could be avoided.

Figs. 1–3 show a simple example that provides an exact explanation of the redundancy scheduling of two interconnected SPPs in a petrochemical corporation. SPP1 consists of three boilers and three turbines, and SPP2 consists of two boilers and two turbines. The pipe connections between SPP1 and SPP2 provide flexibility for the utility supply and backup for each other. The loads of the turbine and letdown valve are assumed to be adjusted quickly within the process buffer time. The optimal operating scheme is achieved using the conventional optimization method (Fig. 1a). As shown in Fig. 1a, the economic optimal load rates of the three boilers in SPP1 are 0%, 100%, and 100%, and the economic optimal load rates of the two boilers in SPP2 are 100% and 0%, respectively. The economic optimal loads of the three turbines in SPP1 are 100%, 0%, and 100%, and the economic optimal loads of the two turbines in SPP2 are 100% and 100%, respectively. When one of the operating boilers (e.g., B1.2) fails unexpectedly, starting up the cold backup equipment (e.g., B1.1 or B2.2) is impossible because the time duration (e.g., at least two hours for the boilers) of the start-up process is much longer than the process buffer time (a few minutes). The operating boilers do not have enough spare loads to increase their generation to compensate for the shortage in utility energy supply (Fig. 1b), although T1.3 and T2.2 have decreased to their minimum loads. The supply of HP in SPP1 and the supply of HP and MP in SPP2 are insufficient, and thus some of the processes must be shut down or the production rate must be decreased. The large power importation of 13.88 MW not only affects the safety of the local

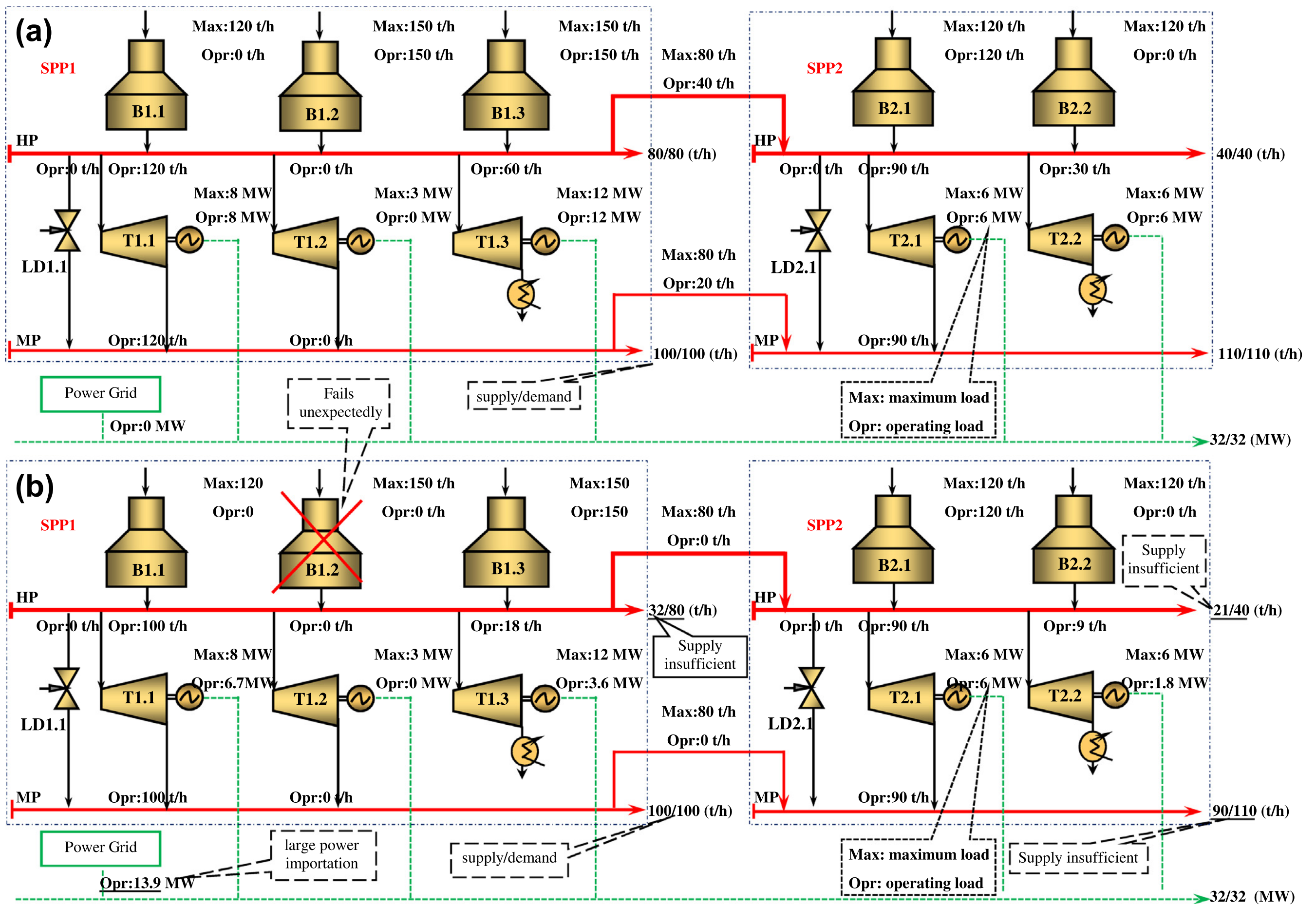

Fig. 1. An economic operation scheme of the SPPs without considering equipment failure: (a) balances under normal operating; (b) balances when one boiler unexpectedly shut down.

power grid but also increases the fixed power electricity charge because of the high backup capacity from the local power grid. Therefore, the economic optimal operation scheme based on the conventional method is infeasible for equipment failure conditions.

Fig. 2a shows a feasible operation redundancy scheme that can cope with emergency conditions. The scheduled load rates of the three boilers in SPP1 are 75%, 80%, and 80%, and those of the two boilers in SPP2 are 75% and 0%, respectively. The scheduled load rates of the three turbines in SPP1 are 100%, 0%, and 100%, and those of the two turbines in SPP2 are 100% and 100%, respectively. The HP steam and MP steam transportation from SPP1 to SPP2 are 70 t/h and 20 t/h, respectively. When a boiler (e.g., B1.2) fails, the load rates of the operating boilers (i.e., B1.1, B1.3, and B2.1) are increased to 100% within 3 min (the boiler load increasing rate is 10 t/min), as shown in Fig. 2b. The load rates of the three turbines in SPP1 are adjusted to 100%, 0%, and 50%, respectively, and those of the turbines in SPP2 are not changed. Power generation decreases because of the decrease in the inlet steam of T1.3, and only 6 MW of electric power is consequently imported from the local power grid. The HP steam and MP steam from SPP1 to SPP2 are adjusted to 40 t/h and 20 t/h, respectively. By doing so, all the utility energy demands are met for emergency conditions.

As shown in the demonstration example, the utility energy shortage under emergency circumstances can be compensated by the following strategies: (1) increasing the load rates of the operating boiler, (2) decreasing the condensing load of the turbine to save steam, (3) adjusting the inter-plant steam pipe transportation load and letdown valve loads to utilize the redundant load of other interconnected SPPs, and (4) importing more power from the local power grid to compensate for the power production deficiency caused by the decrease in steam condensing. However, Fig. 2a only demonstrates a feasible solution to cope with emergency conditions. A scheme with the same operation redundancy (i.e., 120 t/h) as that in Fig. 2 may not be feasible, as shown in Fig. 3. When B1.2 unexpectedly fails, the loads of B1.1 and B1.3 increase to 90 and 130, respectively, within 3 min. The inter-plant steam supplies remain the same. Although T1.3 reaches its minimum load, and the power importation increases to 8.4 MW, 38 t/h of the HP steam in SPP1 remains short.

As shown in Figs. 1 and 2, the steam pipe connections between these SPPs or production plants improve the operation flexibility by supplying energy or providing backup redundancy for each other. However, plant engineers usually operate the system or consider operation redundancy individually for every SPP based on their experience. As a result, great economic optimization potential is missed out, and excessive operation redundancy for the whole SPP is scheduled, even failed to cope with the equipment failure emergency. Therefore, it is impossible to maintain the economical and safe operation of these SPPs by relying only on experience and the conventional operational planning optimization package. The particular features of the proposed optimization model in this paper are capable of accomplishing the following tasks: (1) determining the operation scenarios under both normal and emergency conditions, (2) optimizing the operating load of boilers, turbines, and letdown valves under both normal and emergency conditions, (3) determining the optimal inter-plant steam supply loads under

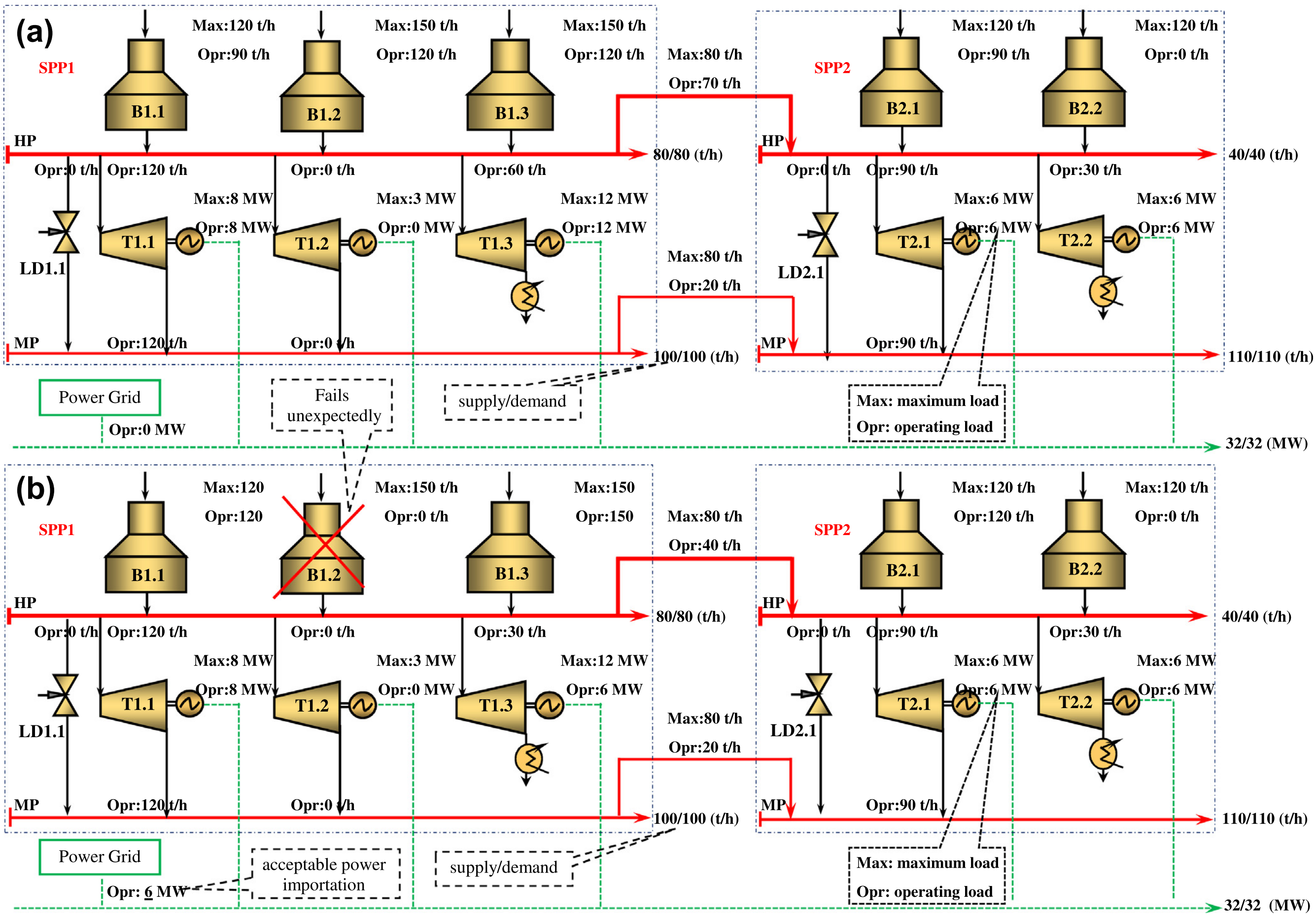

Fig. 2. An feasible operation scheme of the SPPs considering f equipment failure: (a) balances under normal operating; (b) balances when one boiler unexpectedly shut down.

both normal and emergency conditions, and (5) optimizing power importation under both normal and emergency conditions. The objective function is the minimization of the total economic and environmental costs. The decision variables are (1) the operating load of boilers, turbines, interconnected pipes, and letdown valves under both normal and emergency circumstances, and (2) the maximum power importation of each period.

3. Operation scenario specification

The specification of the various scenarios to represent the different operating conditions is a basic element for addressing the issues of equipment availability in an SPP operation. The operating scenarios of an SPP operation optimization problem can be classified into two types. The first type is the real (i.e., certain) operation period that indicates the planning of foreseeable operation conditions, and it usually exists in seasonal periods. This certain condition is identified by the real period index t. The other type is the virtual (i.e., uncertain or unexpected) operation scenario that indicates the unexpected circumstances and behaviors in emergency circumstances. This uncertain (i.e., unexpected) condition is identified by the virtual period index st. Note that emergency (i.e., unexpected) circumstances may occur in all or parts of the real periods. Thus, the virtual scenarios can be identified using indices (t, st), as shown in Fig. 4. The current study aims to optimize the operation to not only meet the utility energy demand at real period t, but also to reserve enough redundancy for the handling of virtual periods (t, st) through a simultaneous optimization routine. Eq. (1) shows the expression of the time duration (P) allocation for each real period t, and Eq. (2) shows the expression of the time duration allocation for each virtual period (t, st). Eq. (3) indicates that the sum of all the time duration percentages θ of real and virtual periods is equal to 1.

$$P_t = \theta_t HR \tag{1}$$

$$P_{t,st} = \theta_{t,st} HR \tag{2}$$

$$\sum_t \left(\sum_{st} \theta_{t,st} + \theta_t \right) = 1 \tag{3}$$

4. Model formulation

4.1. Operational model of real period t

4.1.1. Component performance models of real period t

The SPPs in large petrochemical complexes contain multi-fuel boilers and complex turbines with multiple extractions. Most of the conventional applications dealing with the synthesis and design of SPPs have either simply focused on the mass and energy balance calculations or assumed the constant equipment efficiency. Bahadori and Vuthaluru [27] proposed a simple and effective tool for the prediction of steam rate, turbine efficiency, and the inlet and exhaust nozzle diameters to determine the actual steam rate and total steam requirements for both multi-stage and single-stage turbines. The formulated model is effective for the turbine with a maximum inlet steam pressure of 12 MPa and maximum load of 10 MW. Badyda et al. [28] presented a simple mathematical model of an extraction-condensing turbine, which

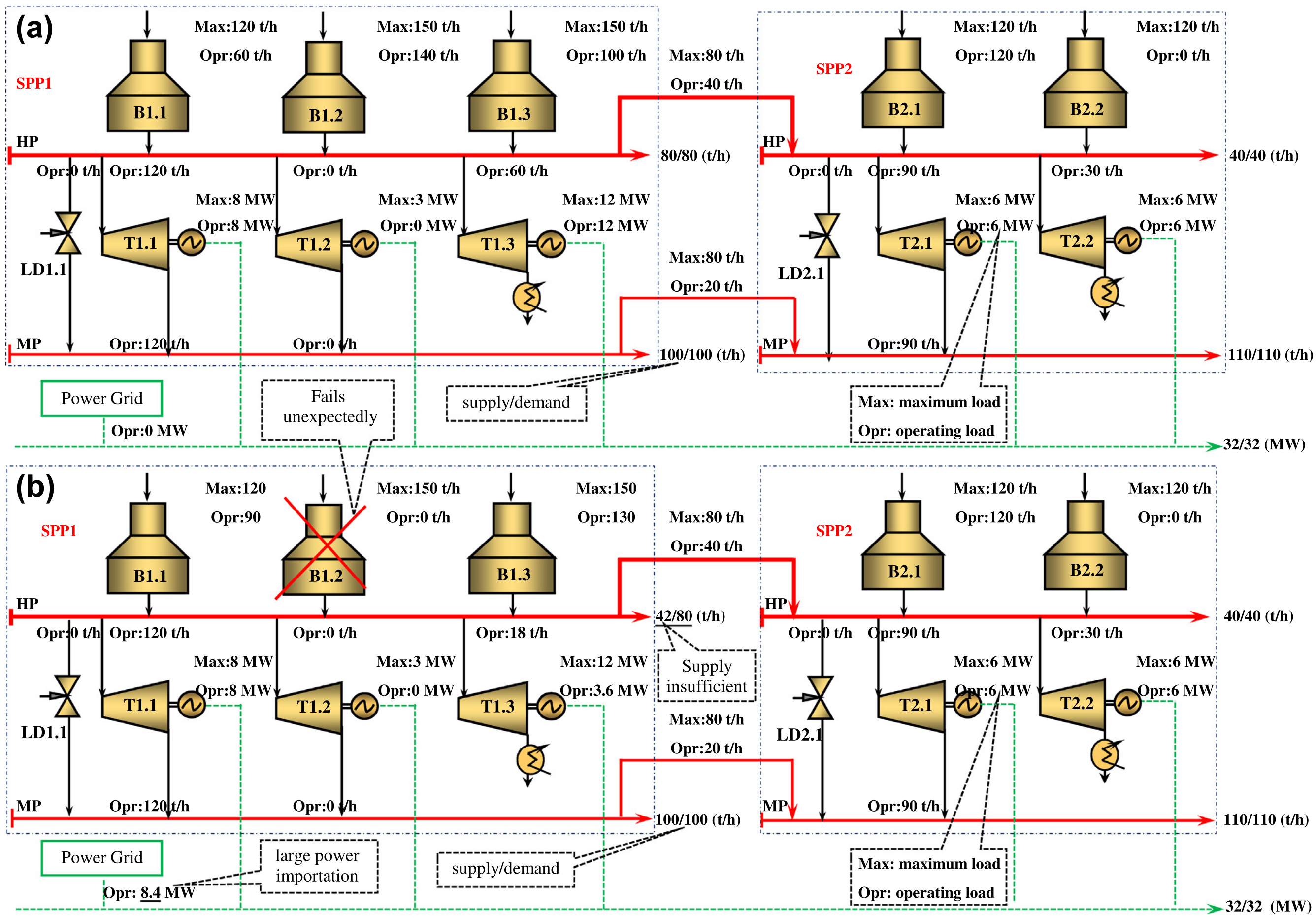

Fig. 3. An infeasible operation scheme of the SPPs even considering equipment failure: (a) balances under normal operating; (b) balances when one boiler unexpectedly shut down.

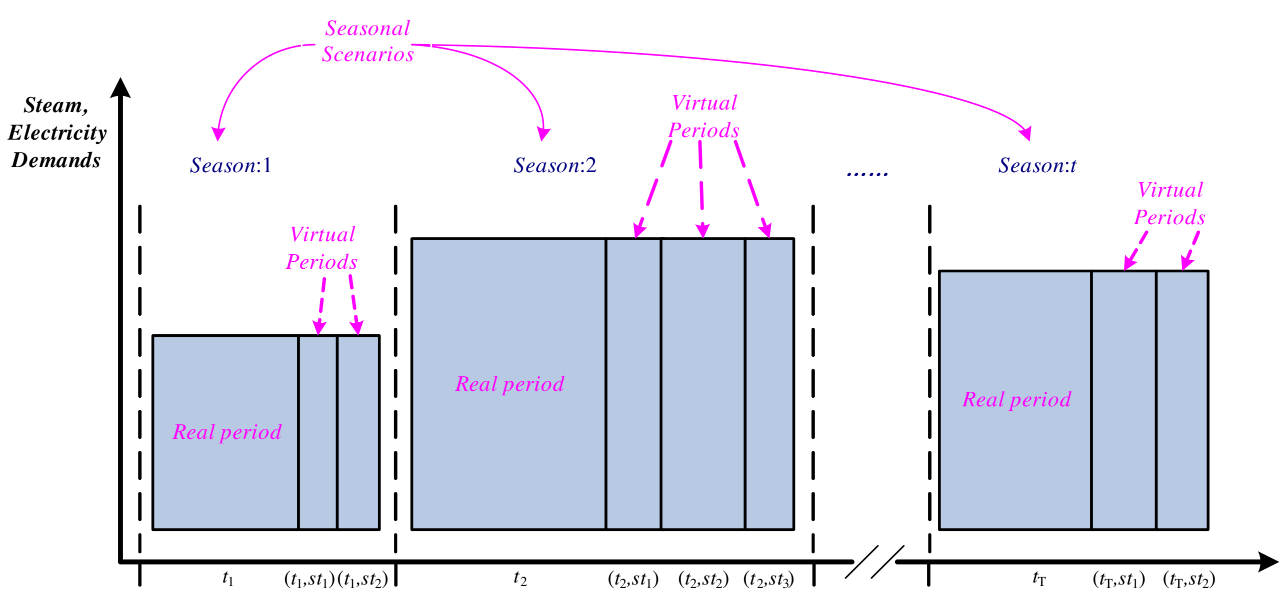

Fig. 4. Scenario specification representation.

is a combination of separate models of a back pressure and a condensing turbine. However, the uncontrolled extraction steams for boiler feedwater preheating are not considered in their proposed model. The uncontrolled extraction steams used for preheating BFW takes up 20%–30% of the total turbine inlet steam in mass flow rate [29]. The other more accurate simulation models [30–32] are strongly nonlinear. The disadvantage of using nonlinear performance models is that the problem becomes a large mixed-integer

nonlinear problem. As discussed in Sections 2 and 3, the operation scenarios are very large when considering equipment failure. Therefore, problem solving becomes more difficult, and a much longer computation time is required compared with that in linear functions. Moreover, the global optimum cannot be guaranteed. The regressed equipment performance model formulated in [33] is then applied in this paper. Moreover, the MILP models with multiple time periods show that the linear approximations do not present a significantly negative effect on the solution of real-world examples [17,33].

Industrial boilers usually generate steam at the required pressure and temperature by transferring the heat from the combustion of fuel or a fuel mixture to the water/steam circuit. Therefore, boiler performance depends on the equipment type and fuel types aside from the equipment size and operating load. Eq. (4) gives an improved industrial boiler model [33] in which fuel consumption and steam production are in a linear relationship. For a safe operation, Eq. (5) constrains the boiler loads to be lower than the upper bound (i.e., maximum steam load) and greater than the lower bound (i.e., minimum safe operating load or economical operating load).

$$\sum_k F_{i,bn,k,t} q_k = a_{i,bn} + b_{i,bn} M^s_{i,bn,t} \tag{4}$$

$$M^{s,L}_{i,bn} Y_{i,bn,t} \leqslant M^s_{i,bn,t} \leqslant M^{s,U}_{i,bn} Y_{i,bn,t} \tag{5}$$

Turbines are usually employed in a steam power plant to directly satisfy shaft demands from large pieces of equipment (e.g., pumps, fans, and compressors) or to produce electricity by driving the generators. The operation of a simple steam turbine (i.e., single back pressure or condense turbine) can be described accurately by the Willans line, which provides a linear relation between the steam flow rate M and the power output E of the turbine [34] (Fig. 5). In industrial SPPs, some steam turbines are designed with multiple controlled extractions to provide steam at different headers for production processes and uncontrolled extractions for feedwater regenerative heating. Analogous to the simple turbine, the inlet steam flowrate M for an extraction turbine can be expressed as a function of power output E and steam extraction S (Fig. 5). Note that

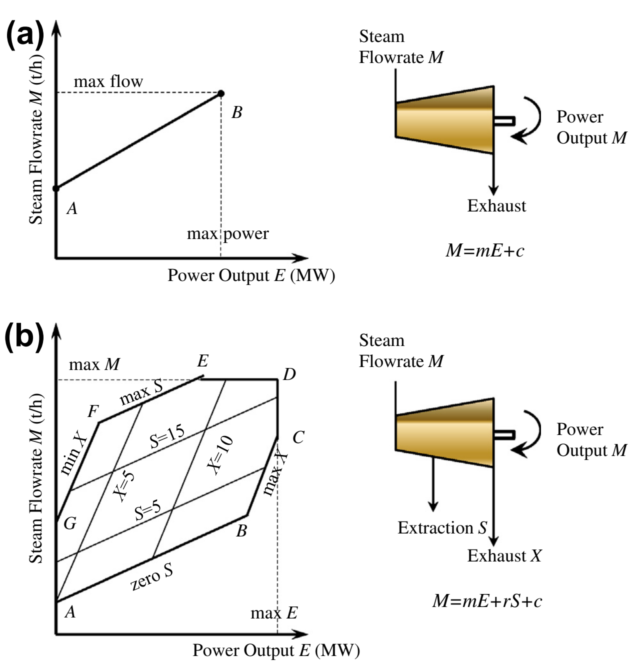

Fig. 5. The performance diagram for: (a) a simple turbine and (b) an extraction turbine.

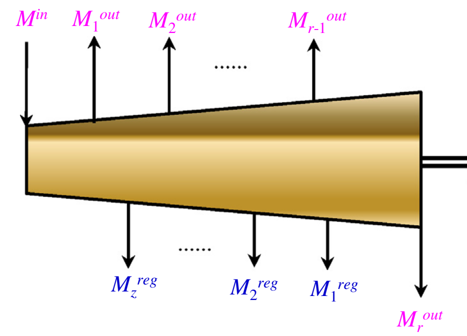

Fig. 6. General multiple extractions turbine representation.

most of manufacturer-provided turbine performance curves are drawn based on this concept. Fig. 6 shows the general structure of a complex turbine having multiple controlled extractions (i.e., M^{out}_1, M^{out}_2, ... in Fig. 6) and multiple uncontrolled extractions (i.e., M^{reg}_1, M^{reg}_2, ... in Fig. 6). The mass flow rates of the controlled extractions are determined by the process demands, and the mass flow rates of uncontrolled extractions are directly relevant to the controlled extraction and condensation. Analogous to the model formulated by Mavromatis and Kokossis [34], the operation of the complex turbine is formulated by Eq. (6), which yields the linear relation between electricity generation and mass flow rate of controlled extractions. Eq. (7) shows the mass balance of a complex turbine *tn* in steam power plant *i*. The mass flow rate $M^{s,reg}_{i,tn,z,t}$ of the uncontrolled extraction changes linearly with $M^{s,out}_{i,tn,r,t}$ under the condition of fixed makeup water parameters. The aggregate model of the total mass flow rate of uncontrolled extractions is formulated by Eq. (8). Eqs. (9) and (10) yield the lower and upper steam flow rate limits for inlet and outlet mass flow rate, respectively.

$$E^{gen}_{i,tn,t} = u_{i,tn} + \sum_r v_{i,tn,r} M^{s,out}_{i,tn,r,t} \tag{6}$$

$$M^{s,in}_{i,tn,t} = \sum_r M^{s,out}_{i,tn,r,t} + \sum_z M^{s,reg}_{i,tn,z,t} \tag{7}$$

$$\sum_z M^{s,reg}_{i,tn,z,t} = \rho_{i,tn} + \sum_r \sigma_{i,tn,r} M^{s,out}_{i,tn,r,t} \tag{8}$$

$$M^{s,in,L}_{i,tn} Y_{i,tn,t} \leqslant M^{s,in}_{i,tn,t} \leqslant M^{s,in,U}_{i,tn} Y_{i,tn,t} \tag{9}$$

$$M^{s,out,L}_{i,tn,r} Y_{i,tn,t} \leqslant M^{s,out}_{i,tn,r,t} \leqslant M^{s,out,U}_{i,tn,r} Y_{i,tn,t} \tag{10}$$

4.1.2. Inter-plant steam supply constraints of real period t

To meet the steam quantity and quality demands, the inter-plant steam supply flow rate $M^s_{i,j,r,t}$ (i.e., steam of header r from plant i to plant j) is limited by the pipe transportation capability and the required steam parameters [Eq. (11)]. The amount of transport steam loss from the pressure and the temperature drop is also estimated simply by Eq. (12), where φ and ψ represent the regressed coefficients.

$$M^s_{i,j,r,t} \leqslant M^{s,max}_{i,j,r} \tag{11}$$

$$M^{s,loss}_{i,j,r,t} = \varphi + \psi M^s_{i,j,r,t} \tag{12}$$

4.1.3. Electricity demand constraints of real period t

The total electricity generated by the turbines and imported from the local power grid must be equal to the power electricity demand from the processes [Eq. (13)]. Eq. (14) gives the power importation constraints, where $E^{impE,max}$ is the maximum

allowable power importation and is a decision variable that affects the fixed part of the power electricity importation from the local power grid.

$$E_t^{impE} + \sum_i \sum_{tn} E_{i,tn,t}^{gen} = E_t^{dem} \tag{13}$$

$$E_t^{impE} \leqslant E^{impE,\max} \tag{14}$$

4.1.4. Steam demand constraints of each SPP of real period t

For each production plant, the net supplied steam (i.e., boiler generated steam, net steam from letdown valve, and net steam from turbine) of each steam header must be greater than or equal to the steam demand from the processes [Eq. (15)].

$$\begin{aligned}&\sum_{bn} M_{i,bn,r,t}^{s} + \sum_{tn}(M_{i,tn,r,t}^{s,out} - M_{i,tn,r,t}^{s,in}) + \sum_{ln}(M_{i,ln,r,t}^{s,out} - M_{i,ln,r,t}^{s,in})\\ &\quad + \sum_{j\neq i}(M_{j,i,r,t}^{s} - M_{j,i,r,t}^{s,loss})\\ &\quad \geqslant M_{i,r,t}^{s,dem}\end{aligned} \tag{15}$$

4.2. Operational optimization model and constraints of virtual period st

The equipment performance models of virtual period *st* are analogous to those of the real period, and the variables are denoted by adding superscript *e*. The boiler flow rate increase model and the utility energy demand constraints of the virtual periods are formulated to transform the operation mode from a normal condition to an emergency handling condition.

4.2.1. Boiler flow rate increase model of virtual period st

The steam generation in operating boilers other than the failed boiler increases to compensate for the shortage in steam supply. A mechanical limitation prevents the boilers from increasing steam production drastically, only at a limited rate. Fig. 7 presents the boiler steam generation increase process. Eq. (16) describes the increasing model in steam production at a fixed rate $V_{i,bn}$. The maximum steam production limit of each boiler caused by capacity limitation is another physical constraint, as shown in Eq. (17). The "$\leqslant$" in Eqs. (16) and (17) is a relaxation description that restricts steam generation to the lower value between steam generations calculated using Eq. (16) and capacity limitation.

$$M_{i,bn,t,st}^{e,s} \leqslant M_{i,bn,t}^{s} + V_{i,bn}T \tag{16}$$

$$M_{i,bn,t,st}^{e,s} \leqslant M_{i,bn}^{s,\max} Y_{i,bn,t}^{s} \tag{17}$$

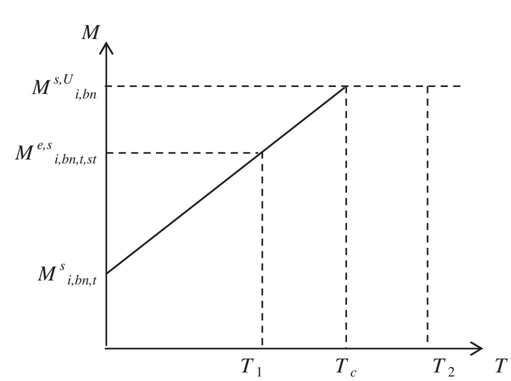

Fig. 7. Boiler flow rate increase model representation.

4.2.2. Turbine model of the virtual period

As described in Section 2, the operating turbine is assumed to be adjusted quickly enough to increase or decrease the steam flow rate. Therefore, the turbine models of the real period are also applied to the virtual period and are formulated by Eqs. (18)–(22). The backup boiler starting up within several minutes of the process buffer time is impossible. Therefore, the operating status of turbines should be constrained by adding logic constraints formulated by Eq. (23).

$$E_{i,tn,t,st}^{e,gen} = u_{i,tn} + \sum_r v_{i,tn,r} M_{i,tn,r,t,st}^{e,s,out} \tag{18}$$

$$M_{i,tn,t,st}^{e,s,in} = \sum_r M_{i,tn,r,t,st}^{e,s,out} + \sum_z M_{i,tn,z,t,st}^{e,s,reg} \tag{19}$$

$$\sum_z M_{i,tn,z,t,st}^{e,s,reg} = \rho_{i,tn} + \sum_r \sigma_{i,tn,r} M_{i,tn,r,t,st}^{e,s,out} \tag{20}$$

$$M_{i,tn}^{s,in,L} Y_{i,tn,t,st}^{e} \leqslant M_{i,tn,t,st}^{e,s,in} \leqslant M_{i,tn}^{s,in,U} Y_{i,tn,t,st}^{e} \tag{21}$$

$$M_{i,tn,r}^{s,out,L} Y_{i,tn,t,st}^{e} \leqslant M_{i,tn,r,t,st}^{e,s,out} \leqslant M_{i,tn,r}^{s,out,U} Y_{i,tn,t,st}^{e} \tag{22}$$

$$Y_{i,tn,t,st}^{e} \leqslant Y_{i,tn,t} \tag{23}$$

4.2.3. Electricity demand constraints of the virtual period

The power generation of failed turbines are eliminated from power balances [see Eq. (24)] and the power importation is less than or equal to the maximum allowable power importation for virtual period [see Eq. (25)].

$$E_{t,st}^{e,impE} + \sum_i \sum_{tn\neq sttn} E_{i,tn,t,st}^{e,gen} = E_t^{dem} \tag{24}$$

$$E_{t,st}^{e,impE} \leqslant E^{impE,\max} \tag{25}$$

4.2.4. Steam demand constraints of each SPP of virtual periods

The steam flow rates of failed boilers and/or turbines are eliminated from the steam balances and are formulated by the following equation:

$$\begin{aligned}&\sum_{bn\neq stbn} M_{i,bn,r,t,st}^{e,s} + \sum_{tn\neq sttn}(M_{i,tn,r,t,st}^{e,s,out} - M_{i,tn,r,t,st}^{e,s,in}) + \sum_{ln}(M_{i,ln,r,t,st}^{e,s,out}\\ &\quad - M_{i,ln,r,t,st}^{e,s,in}) + \sum_{j\neq i}(M_{j,i,r,t,st}^{e,s} - M_{j,i,r,t,st}^{e,s,loss})\\ &\quad \geqslant M_{i,r,t}^{s,dem}\end{aligned} \tag{26}$$

4.3. Objective function

The objective of the optimization model considering equipment failure is to minimize the total cost [Eq. (27)] of SPPs and to satisfy the varying steam and electricity demands of the processes under both real and virtual periods. The total cost of the SPP [Eq. (27)] is composed of the following: (1) fuel consumption cost of the boiler [first term on the right side of Eq. (27)], (2) equipment maintenance cost and depreciation expense [second term on the right side of Eq. (27)], (3) cost of imported electricity [third term on the right side of Eq. (27)], (4) fixed power importation charge for power importation capacity backup [fourth term on the right side of Eq. (27)], (5) operating cost and material consumption cost of pollutant abatement equipment [fifth term on the right side of Eq. (27)], and (6) emission charge [last term on the right of Eq. (27)]. A detailed description and explanation of the crisp model and pollution model can be found in literature [33].

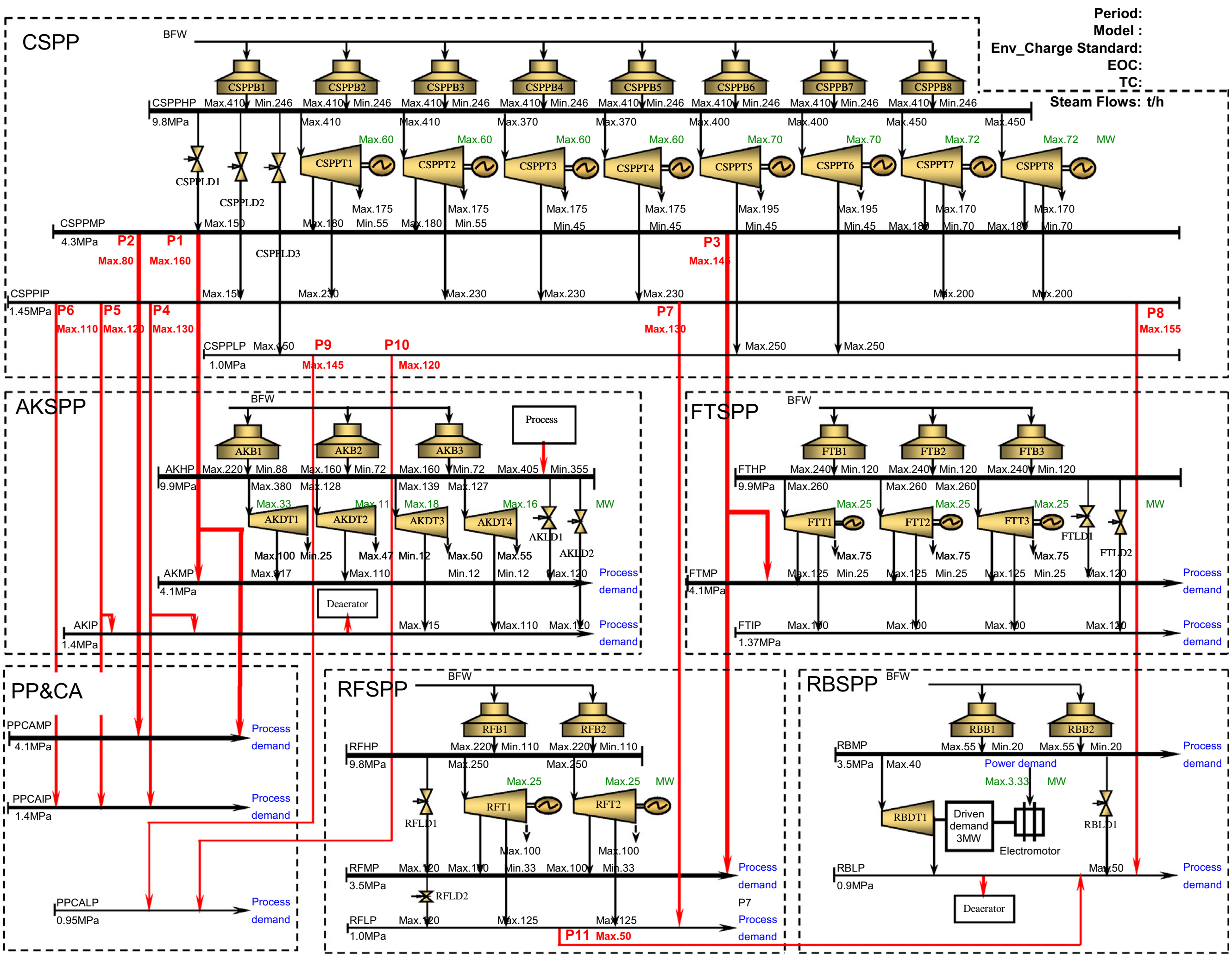

Fig. 8. Flowsheet of SPPs in a petrochemical complex.

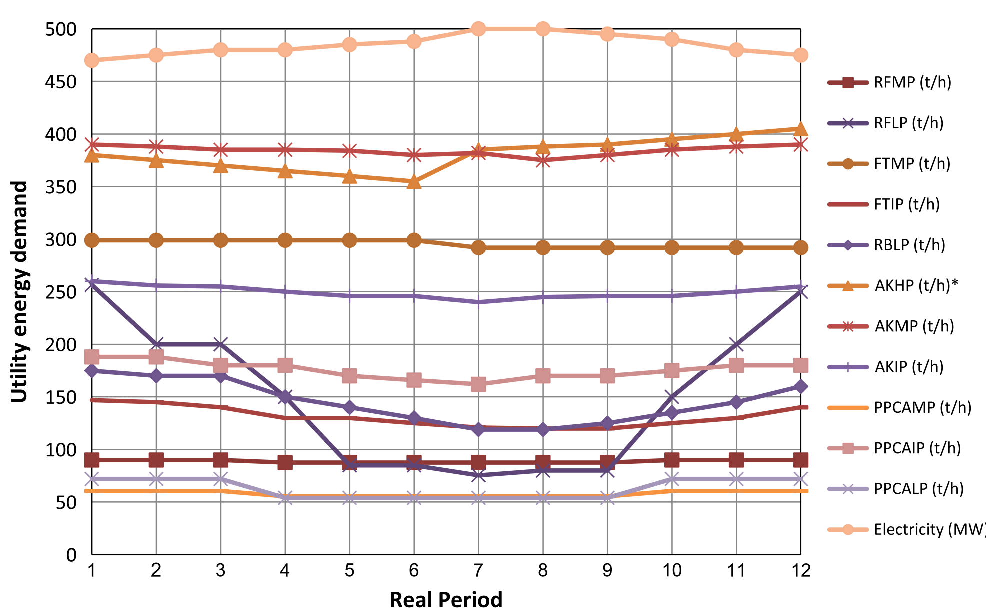

Fig. 9. Steam and power demand of 12 real periods * steam byproduct from waste recovery of AK process.

Table 1
Fuel data.

Fuel	Boiler	*S* (%)	*N* (%)	*CN* (%)	*A* (%)	*LHV* (kJ/kg)	*C* (¥/GJ)
Bituminous coal 1	PCFB in CCSP	0.80	1.20	65.00	22.00	21,736	36,805
Natural gas	GFB in AKSPP	0.10	1.20	75.38	0.00	44,000	61,364
Bituminous coal 2	CFB in RFSPP and FTSPP	2.00	1.00	48.40	18.00	18,400	38,043
Coal–water slurry	CWSB in RBSPP	0.27	0.96	50.17	5.42	17,974	47,291

S, *N*, *CN*, *A*: mass content of sulfur, nitrogen, carbon and ash in fuel; LHV: low heat value; *C*: specific price of fuels.

Table 2
Optimal operation scheme (SPPOSNEF) of boiler steam generation, turbine power generation, and pipe transportation in the planning horizon without considering equipment failure.

Operation load	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
CSPPB1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CSPPB2 (t/h)	246.0	246.0	252.8	253.7	246.0	246.0	246.0	246.0	246.0	278.5	322.9	246.0
CSPPB3 (t/h)	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0
CSPPB4(t/h)	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0
CSPPB5 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CSPPB6 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CSPPB7 (t/h)	410.0	404.0	410.0	410.0	382.2	371.4	410.0	410.0	410.0	410.0	410.0	377.4
CSPPB8 (t/h)	370.7	410.0	410.0	410.0	410.0	410.0	374.6	387.3	372.9	410.0	410.0	410.0
AKB1 (t/h)	201.9	205.4	208.2	213.2	217.5	219.6	191.0	183.0	184.6	183.2	180.4	176.9
AKB2 (t/h)	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0
AKB3 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AKLD1(t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AKLD2(t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RFB1 (t/h)	179.5	110.0	110.0	220.0	0.0	220.0	0.0	0.0	220.0	0.0	0.0	161.7
RFB2 (t/h)	220.0	215.5	215.5	0.0	220.0	0.0	220.0	220.0	0.0	220.0	220.0	220.0
RFLD1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RFLD2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.4	0.0
FTB1 (t/h)	240.0	202.0	240.0	204.7	240.0	195.8	240.0	240.0	240.0	240.0	187.3	240.0
FTB2 (t/h)	204.9	240.0	195.0	240.0	240.0	240.0	240.0	201.0	240.0	205.2	240.0	185.9
FTB3 (t/h)	240.0	240.0	240.0	240.0	188.8	240.0	201.9	240.0	201.0	240.0	240.0	240.0
FTLD1(t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FTLD2(t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RBB1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RBB2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RBLD1(t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P1 to AK (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P1 to PPCA (t/h)	71.2	0.0	71.2	66.2	66.2	0.0	0.0	0.0	66.2	71.2	71.2	0.0
P2 to PPCA (t/h)	0.0	71.2	0.0	0.0	0.0	66.2	66.2	66.2	0.0	0.0	0.0	71.2
P3 to RF (t/h)	10.2	0.0	0.0	0.0	0.0	0.0	21.9	21.9	7.4	8.5	29.8	0.0
P3 to FT (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P4 to AK (t/h)	70.3	0.0	86.1	0.0	78.4	0.0	0.0	0.0	0.0	73.2	76.8	81.3
P4 to PPCA (t/h)	0.0	100.1	0.0	92.0	51.6	36.6	22.2	34.1	81.9	0.0	0.0	0.0
P5 to AK (t/h)	19.9	86.7	0.0	81.8	0.0	78.7	68.3	72.2	73.4	0.0	0.0	0.0
P5 to PPCA (t/h)	100.1	0.0	92.0	0.0	30.3	41.3	51.7	47.8	0.0	120.0	92.0	92.0
P6 to PPCA (t/h)	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	77.0	110.0	110.0
P7 to RF (t/h)	130.0	130.0	130.0	108.8	86.7	86.7	77.0	81.6	81.6	130.0	130.0	130.0
P8 to RB (t/h)	155.0	155.0	155.0	153.1	142.9	132.7	121.4	121.4	127.6	137.8	148.0	155.0
P9 to PPCA (t/h)	72.7	72.7	72.7	54.5	0.0	0.0	0.0	0.0	54.5	72.7	72.7	72.7
P10 to PPCA (t/h)	0.0	0.0	0.0	0.0	54.5	54.5	54.5	54.5	0.0	0.0	0.0	0.0
P11 to RB (t/h)	23.6	18.5	18.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.3
CSPPT1 (MW)	59.3	49.5	54.3	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
CSPPT2 (MW)	34.8	58.5	59.5	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	43.2
CSPPT3 (MW)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
CSPPT4 (MW)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
CSPPT5 (MW)	70.0	0.0	70.0	0.0	0.0	70.0	70.0	70.0	70.0	70.0	0.0	70.0
CSPPT6 (MW)	0.0	70.0	0.0	70.0	70.0	0.0	0.0	0.0	0.0	0.0	70.0	0.0
CSPPT7 (MW)	35.6	35.6	35.6	35.6	35.6	35.6	42.6	42.6	35.6	35.6	35.6	35.6
CSPPT8 (MW)	35.6	35.6	35.6	40.9	40.9	40.9	35.6	35.6	41.5	42.0	43.7	35.6
RFT1 (MW)	25.0	16.4	16.4	25.0	10.2	10.2	15.1	15.1	25.0	10.2	0.0	25.0
RFT2 (MW)	25.0	25.0	25.0	0.0	24.1	24.1	25.0	25.0	11.2	20.6	25.0	22.4
FTT1 (MW)	18.5	18.2	17.4	21.8	18.0	20.6	25.0	25.0	25.0	25.0	19.0	17.2
FTT2 (MW)	25.0	24.5	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
FTT3 (MW)	24.5	25.0	24.5	25.0	24.5	25.0	25.0	25.0	25.0	25.0	25.0	24.2
PowerBuyMax (MW)[a]	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0

[a] The plant engineer planned power importation contract.

$$
\begin{aligned}
MinOBJ = & \sum_{i}\sum_{bn}\sum_{k}\sum_{t}\left(F_{i,bn,k,t}P_t + \sum_{st}F^{e}_{i,bn,k,t,st}P_{t,st}\right)C^{f}_{k} \\
& + \sum_{n}\sum_{t}\left(M_{n,t}P_t + \sum_{st}M_{n,t,st}P_{t,st}\right)O_n \\
& + \sum_{t}C^{impE}\left(E^{impE}_{t}P_t + \sum_{st}E^{e,impE}_{t,st}P_{t,st}\right) \\
& + \sum_{t}C^{fix,impE}E^{impE,\max}_{t} \\
& + \sum_{i}\sum_{bn}\sum_{d}\sum_{t}(CA_{i,bn,d} + OA_{i,bn,d})\left(GA_{i,bn,d,t} + \sum_{st}GA^{e}_{i,bn,d,t,st}\right) \\
& + \sum_{i}\sum_{bn}\sum_{d}\sum_{t}\left(G_{i,bn,d,t}P_t + \sum_{st}G_{i,bn,d,t,st}P_{t,st}\right)C_d
\end{aligned}
\tag{27}
$$

The objective functions [(27)] that incorporate the constraints [Eqs. (1)–(26)] and the pollutant emission model in literature [33] represent a multi-period MILP model (SPPOSEF). The MILP models were formulated using GAMS 23.6 on a 3.0 GHz Intel(R) Core(TM) 2 PC. The code CPLEX in GAMS 23.6 was used to solve the MILP models [35].

5. Case study

5.1. Case description

The large interconnected SPPs (Fig. 8) in a petrochemical complex in China referenced from Luo et al. [33] are taken as a case to validate the proposed methodology and the formulated model. The SPPs are composed of one centralized steam power plant (CSPP) and four decentralized SPPs (i.e., AKSPP, RFSPP, FTSPP, and RBSPP located in alkene (AK), refinery (RF), fertilizer (FT), and rubber (RB), respectively, as shown in Fig. 8).

The CSPP is composed of eight pulverized coal-fired boilers (PCFBs) and eight extraction condensing turbines. The task of the CSPP is to supply electricity and steam of different headers to all production plants through 10 steam pipes (P1–P10 in Fig. 8). In AKSPP, the HP steam is supplied by the processing produced steam and by three gas-fired boilers (GFBs). Note that the cold backup boiler AKB3 (identical to AKB2) in Ref. [33] is put into operation in this study to cope with the emergency circumstances. Four turbines driven by the AKHP are designed to provide driven power for the processes. The RFMP in the RF and the FTMP in the FT are supplied by turbine extractions and by the CSPP (through P3). The RFLP is supplied by turbine extractions and/or by the CSPP (through P8). In the RBSPP, two small coal–water slurry-fired boilers (CWSB) are designed to supply the RBMP steam for a 3 MW-driven turbine RBT1. The driven power can also be provided by an electromotor with an isentropic efficiency of 90% (i.e., the maximum power consumption of a 3.33 MW electromotor). The RBLP is supplied by RBDT1, CSPP (through P8), and RFSPP (through P11). The equipment (i.e., boiler, turbine, letdown valve, and inter-plant steam pipe) design load data (i.e., maximum and minimum steam generation of boilers, maximum and minimum inlet and outlet steam flow rate of turbines, maximum power generation of turbines, maximum steam flow rate of letdown valves, and inter-plant steam pipe transportation limits) of all the SPPs are presented in Fig. 8. The steam and electricity demands of the six production plants are given in Fig. 9. The total annual working hours are 8400 and are divided into 12 real periods with 700 h each period. The import price of power electricity is 0.6 ¥/kW h. The fuel data, including fuel type, fuel composition, fuel LHV, and specific fuel price, are listed in Table 1. The boiler and turbine model coefficients regressed from the plant data or performance curves are listed in Tables A.1–A.3. From the data supplied by plant engineers, the averagely allocated statistical maintenance and depreciation cost for the PCFB, GSB, CFBB, and WCFB are 40, 36, 42 and 42 ¥/t, respectively. The maintenance and depreciation cost for turbine is neglected because it is considered minor compared with that for boiler and because the difference between turbines is very small. The pollutant emission charge for dust, NOx, SO2, and CO2 are 2200, 8000, 6000 and 23 ¥/t, respectively. The price of limestone with 92.3% CaCO3 content, which is used for desulfurization in the CFBB, is 280 ¥/t. The plant engineering planned maximum power electricity importation is 70 MW throughout a year. More detailed descriptions of the SPPs and the pollutant emission model of the different boilers as well as the model coefficients were not included in the paper because of the limited space. The detailed information can be found in Ref. [33].

5.2. The scheme without considering equipment failure

The SPP operational planning optimization MILP models without considering equipment failure developed by Luo et al. [33]

Table 3
The operaion feasiblity of handling equipment failure periods for scheme SPPOSNEF.

Failed equipment	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
CSPPB1	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]
CSPPB2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CSPPB3	N	N	N	N	N	N	N	N	N	N	N	N
CSPPB4	N	N	N	N	N	N	N	N	N	N	N	N
CSPPB5	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]
CSPPB6	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]
CSPPB7	N	N	N	N	N	N	N	N	N	N	N	N
CSPPB8	N	N	N	N	N	N	N	N	N	N	N	N
CSPPT1–8	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
AKB1–2	N	N	N	N	N	N	N	N	N	N	N	N
AKB3	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]
RFB1	Y	Y	N	Y[b]	Y[a]	Y[b]	Y[b]	Y[b]	Y[a]	Y[a]	N	Y
RFB2	Y	N	Y	Y[a]	Y[b]	Y[a]	Y[a]	Y[a]	Y[b]	Y[b]	Y[a]	Y
RFT1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
RFT2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
FTB1–3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
FTT1–3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

[a] Not in operation.
[b] One turbine in RFSPP is shutdown to save condensing steam or no RFHP steam supplied from boilers.

include 4481 variables and 5293 equations. Table 2 gives the optimal scheme SPPOSNEF with minimum economic and environmental costs. As discussed in Ref. [33], the pieces of equipment are scheduled according to their economic and environmental features. The boiler loads differ significantly from one another in terms of performance behavior. The boilers with higher efficiency and lower environmental impact are operated with a high load, whereas the boilers with lower efficiency and higher environmental impact are shut down for backup or are operated with a low load. Therefore, the equipment operation load rates are different and usually have a high gap between different equipment with the same SPP. These results are optimal under the criteria of economic cost and environmental impact but may not be reasonable for operation considering equipment failure. The failure of a boiler with a high operation load results in large steam deficiency. Although the boiler with a lower load reserves much load redundancy, it can only utilize part of the spare load capacity within the process buffer time. Table 3 gives the scheme flexibility for coping with an equipment failure situation. As shown in Table 3, it is infeasible to handle the emergency situations of CSPPB3–4 and 7–8 failures because of their high operating load and the small spare capacity of the whole plant. In AKSPP, it is infeasible to handle the failure conditions of any of the boilers because of the strict steam demand of the driving turbines. In RFSPP, it is infeasible to handle the failure situations of boiler RFB1 during period T11. Although it is feasible to handle the boiler failure situations during

Table 4
Plant engineers planed operation scheme (SPPEPNEF) of boiler steam generation, turbine power generation, and pipe transportation in the planning horizon without considering equipment failure.

Operation load	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
CSPPB1 (t/h)	0.0	348.4	349.2	358.7	378.4	376.2	357.5	0.0	0.0	364.5	346.2	349.2
CSPPB2 (t/h)	0.0	0.0	349.2	358.7	378.4	376.2	357.5	377.4	0.0	0.0	346.2	349.2
CSPPB3 (t/h)	364.5	0.0	0.0	358.7	378.4	376.2	357.5	377.4	376.8	0.0	0.0	349.2
CSPPB4(t/h)	364.5	348.4	0.0	0.0	378.4	376.2	357.5	377.4	376.8	364.5	0.0	0.0
CSPPB5 (t/h)	364.5	348.4	349.2	0.0	0.0	376.2	357.5	377.4	376.8	364.5	346.2	0.0
CSPPB6 (t/h)	364.5	348.4	349.2	358.7	0.0	0.0	357.5	377.4	376.8	364.5	346.2	349.2
CSPPB7 (t/h)	364.5	348.4	349.2	358.7	378.4	0.0	0.0	377.4	376.8	364.5	346.2	349.2
CSPPB8 (t/h)	364.5	348.4	349.2	358.7	378.4	376.2	0.0	0.0	376.8	364.5	346.2	349.2
AKB1 (t/h)	175.5	175.5	175.5	175.5	175.5	175.5	175.5	175.5	175.5	175.5	175.5	175.5
AKB2 (t/h)	128.0	128.0	128.0	128.0	128.0	128.0	128.0	128.0	128.0	128.0	128.0	128.0
AKB3 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AKLD1(t/h)	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
AKLD2(t/h)	13.6	9.6	0.6	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	0.6
RFB1 (t/h)	158.3	179.1	179.1	0.0	0.0	0.0	172.5	0.0	0.0	0.0	179.1	197.5
RFB2 (t/h)	158.3	179.1	179.1	220.0	220.0	220.0	172.5	220.0	220.0	220.0	179.1	197.5
RFLD1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RFLD2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	21.9	0.0	0.0	0.0	0.0	63.9
FTB1 (t/h)	228.3	227.3	225.0	220.3	240.0	240.0	240.0	240.0	240.0	214.9	217.3	222.0
FTB2 (t/h)	228.3	227.3	225.0	220.3	240.0	240.0	240.0	240.0	240.0	214.9	217.3	222.0
FTB3 (t/h)	228.3	227.3	225.0	220.3	0.0	0.0	0.0	0.0	0.0	214.9	217.3	222.0
FTLD1(t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FTLD2(t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RBB1 (t/h)	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
RBB2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RBLD1(t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P1 to AK (t/h)	105.0	98.9	86.8	86.2	85.2	81.1	103.4	76.1	81.1	86.2	89.2	91.9
P1 to PPCA (t/h)	0.0	0.0	0.0	0.0	66.2	66.2	56.6	0.0	0.0	71.2	70.8	68.1
P2 to PPCA (t/h)	71.2	71.2	71.2	66.2	0.0	0.0	9.5	66.2	66.2	0.0	0.4	3.1
P3 to RF (t/h)	74.1	0.0	0.0	29.4	4.5	4.5	43.4	4.5	4.5	31.9	0.0	0.0
P3 to FT (t/h)	0.0	0.0	0.0	0.0	118.7	113.2	101.6	100.5	100.5	0.0	0.0	0.0
P4 to AK (t/h)	29.9	29.9	38.0	33.6	111.4	29.5	123.2	28.5	111.4	29.5	125.6	38.0
P4 to PPCA (t/h)	100.1	100.1	92.0	92.0	0.0	77.9	0.0	81.9	0.0	87.0	0.0	92.0
P5 to AK (t/h)	120.0	120.0	120.0	120.0	38.1	120.0	0.0	120.0	38.1	120.0	28.0	120.0
P5 to PPCA (t/h)	0.0	0.0	0.0	0.0	81.9	0.0	73.8	0.0	81.9	0.0	92.0	0.0
P6 to PPCA (t/h)	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0	110.0
P7 to RF (t/h)	130.0	110.5	110.5	130.0	86.7	86.7	0.0	81.6	81.6	130.0	110.5	130.0
P8 to RB (t/h)	141.8	136.7	136.7	116.3	106.1	95.9	34.7	84.7	90.8	101.0	111.2	126.5
P9 to PPCA (t/h)	72.7	72.7	72.7	54.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P10 to PPCA (t/h)	0.0	0.0	0.0	0.0	54.5	54.5	54.5	54.5	54.5	72.7	72.7	72.7
P11 to RB (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	50.0	0.0	0.0	0.0	0.0	0.0
CSPPT1 (MW)	0.0	0.0	0.0	0.0	0.0	0.0	60.0	60.0	60.0	0.0	0.0	0.0
CSPPT2 (MW)	49.9	49.2	49.2	49.1	47.4	47.0	58.9	41.0	41.3	48.5	48.5	49.5
CSPPT3 (MW)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
CSPPT4 (MW)	60.0	60.0	60.0	60.0	60.0	60.0	0.0	60.0	60.0	60.0	60.0	60.0
CSPPT5 (MW)	35.5	42.5	45.8	52.4	63.2	65.9	70.0	52.8	49.7	58.8	48.1	43.0
CSPPT6 (MW)	35.5	42.5	45.8	52.4	63.2	65.9	70.0	52.8	49.7	58.8	48.1	43.0
CSPPT7 (MW)	55.5	51.6	51.1	51.9	53.4	52.6	41.4	44.9	45.2	51.4	50.2	51.6
CSPPT8 (MW)	55.5	51.6	51.1	51.9	53.4	52.6	41.4	44.9	45.2	51.4	50.2	51.6
RFT1 (MW)	25.0	25.0	25.0	14.4	14.4	21.0	25.0	14.4	21.0	22.5	25.0	25.0
RFT2 (MW)	25.0	25.0	25.0	22.5	21.0	14.4	25.0	21.0	14.4	14.4	25.0	25.0
FTT1 (MW)	18.5	24.5	17.4	15.9	0.0	0.0	23.3	0.0	23.3	24.5	15.3	16.9
FTT2 (MW)	25.0	18.7	24.5	24.5	23.9	23.6	0.0	23.3	25.0	15.0	24.5	25.0
FTT3 (MW)	24.5	24.5	25.0	25.0	25.0	25.0	25.0	25.0	0.0	24.5	25.0	24.5
PowerBuyMax (MW)[a]	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0

[a] The plant engineer planned power importation contract.

Table 5
The operaion feasiablity of handling equipment failure circumstances for scheme SPPEPNEF.

Failed equipment	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
CSPPB1	Y[a]	Y	Y	Y	Y	Y	Y	Y	Y	Y[a]	Y[a]	Y
CSPPB2	Y[a]	Y[a]	Y	Y	Y	Y	Y	Y	Y	Y	Y[a]	Y[a]
CSPPB3	Y	Y[a]	Y[a]	Y	Y	Y	Y	Y	Y	Y	Y	Y[a]
CSPPB4	Y	Y	Y[a]	Y[a]	Y	Y	Y	Y	Y	Y	Y	Y
CSPPB5	Y	Y	Y	Y[a]	Y[a]	Y	Y	Y	Y	Y	Y	Y
CSPPB6	Y	Y	Y	Y	Y[a]	Y[a]	Y	Y	Y	Y	Y	Y
CSPPB7	Y	Y	Y	Y	Y	Y[a]	Y[a]	Y	Y	Y	Y	Y
CSPPB8	Y	Y	Y	Y	Y	Y	Y[a]	Y[a]	Y	Y	Y	Y
CSPPT1–8	Y	Y	Y	Y	Y	Y	Y	Y[a]	Y[a]	Y	Y	Y
AKB1–2	N	N	N	N	N	N	N	N	Y	N	N	N
AKB3	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]
RFB1	N	Y	Y	Y[a]	Y[a]	Y[a]	Y	Y[b]	Y[b]	Y[b]	Y	Y
RFB2	N	N	Y	Y[b]	N	N	Y	N	N	N	Y	Y
RFT1–2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
FTB1	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y
FTB2	Y	Y	Y	Y	N	N	N	N	N	Y	Y	Y
FTB3	Y	Y	Y	Y	Y[a]	Y[a]	Y[a]	Y[a]	Y[a]	Y	Y	Y
FTT1–3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

[a] Not in operation.
[b] One turbine in RFSPP is shutdown to save condensing steam or no RFHP steam supplied from boilers.

the rest of the periods, one turbine must be shut down to save condensing steam or unavailable of RFHP steam. In FTSPP, it is feasible to handle the failure situations of any of the boilers except during period T11. In period T11, RFSPP imports 29.2 t/h steam from CSPP through P3, and not enough redundancy is left for FTSPP. The economic and environmental cost of the optimal scheme presented in Table 2 is M¥ 4896.4. The total cost is M¥ 4916.6, including the fixed power importation charge of M¥ 20.2.

The scheme SPPEPNEF (Table 4) planned by plant engineers (who rely mainly on their own experience with the equal load allocation principle) is also simulated. The economic and environmental cost is M¥ 5256.2 (i.e., the economic cost is M¥ 4559.99 [33]). The total cost (including the fixed power importation charge of M¥ 20.2) is M¥ 5276.4. Table 5 shows the flexibility of handling the equipment failure situations for scheme SPPEPNEF. As shown in Table 5, the scheme SPPEPNEF lacks flexibility, although it costs 7.32% (M¥ 359.8) more than that of scheme SPPOSNEF.

5.3. The optimal scheme considering equipment failure

The time length of the virtual periods are assumed to be zero for the present case. This assumption is reasonable because the occurrence of equipment failure is indefinite, and the economic consequence has been factored in the objective function, resulting in a surplus operation capacity (redundancy). Another assumption is that only one boiler or turbine fails at a certain time, which is reasonably based on industry data. Although two or more boilers and turbines may fail during the same operational period, the occurrence of two or more boilers failing simultaneously is rare. When one boiler or turbine fails, the operating load of the equipment is adjusted within a few minutes to compensate for the steam shortage, and then the backup boilers or turbines are started. Thus, an SPP may recover its capacity to cope with emergency situations within several hours. The studied SPPs have 18 boilers and 13 power electricity generation turbines. Based on these assumptions, 33 virtual scenarios should be defined to represent the boiler failure circumstances. However, the boiler design loads of the boilers in RBSPP are very small and can be easily compensated when one of the boiler fails. Thererfore, 29 virtual periods for each real period are defined, and the total periods are $12 \times 29 = 348$. The process buffer time is 4 min for the current case. The boiler increase rate is listed in Table 6. The optimization model considering equipment failure is established and solved using GAMS 23.6 with 73229

Table 6
The boiler steam generation increase rate.

Boiler ID	Increase rate (t/min)
CSPPB1–2	12
CSPPB3–4	11
CSPPB5–6	10
CSPPB7–8	11.5
AKB1–3	13
RFB1–2	10
FTB103	10
RBB1–2	11

variables and 106189 equations. The scheme SPPOSEF is achieved with a relative difference of 0.1% in 221.07 CPU seconds (Table 7). As shown in Table 7, five boilers in the CSPP are in operation. In AKSPP, three boilers operate during periods T1-T6 and T10-T12, and the two boilers operate during the rest of the period. All boilers in RFSPP and FTSPP operate with partial loads throughout all periods. For AKSPP, RFSPP, and FTSPP, the utility energy demand is satisfied under both real and virtual periods with the backup redundancy of CSPP. Moreover, the redundancy of CSPP is also reserved by other SPPs, and the CSPP reserving extra redundancy for boiler failure situations is unnecessary. For example, boilers CSPPB3 and CSPPB4 operate at a maximum load (410 t/h). When CSPPB3 or CSPPB4 fails unexpectedly, the steam deficiency of 410 t/h can be compensated by (1) increasing the operating load of the rest of three operating boilers in CSPP and decreasing the condensing steam of turbines in CSPP; (2) increasing the operation load of boilers in RKSPP and decreasing the steam exportation to RKSPP; (3) increasing the steam loads of boilers in RFSPP and reducing the steam extraction through pipe P7; and (4) importing power electricity from the local power grids. In other SPPs, more pieces of equipment are in operation than in schemes SPPOSNEF and SPPEPNEF; therefore, they reserve more operation redundancy. As shown in Table 7, most of the boilers operate under partial load to be ready to increase their load to compensate for the steam shortage due to any of the 29 equipment failure conditions. Therefore, the cost is a little higher than that of SPPOSNEF. The total cost of the scheme is M¥ 4937.5, which is 6.42% less than that of SPPEPNEF and only 0.42% more than that of scheme SPPOSNEF. The additional cost penalty decreases with the decreasing gap between the total capacity of the SPP and the utility demand from the pro-

Table 7
Optimal operation scheme (SPPOSEF) of boiler steam generation, turbine power generation, and pipe transportation in the planning horizon considering equipment failure.

Operation load	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
CSPPB1 (t/h)	0.0	0.0	0.0	312.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CSPPB2 (t/h)	298.7	332.0	344.8	0.0	291.6	280.8	304.1	299.0	292.0	335.6	348.8	305.4
CSPPB3 (t/h)	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0
CSPPB4(t/h)	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0
CSPPB5 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CSPPB6 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CSPPB7 (t/h)	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0
CSPPB8 (t/h)	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0
AKB1 (t/h)	88.0	88.0	88.0	88.0	88.0	88.0	0.0	0.0	0.0	88.0	88.0	88.0
AKB2 (t/h)	160.0	156.2	160.0	130.3	155.0	160.0	160.0	160.0	160.0	160.0	108.0	92.9
AKB3 (t/h)	113.9	121.2	120.2	155.0	134.5	131.6	160.0	160.0	160.0	95.2	144.4	156.0
AKLD1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AKLD2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RFB1 (t/h)	180.0	180.0	164.6	110.0	113.0	110.0	180.0	180.0	180.0	180.0	142.2	201.7
RFB2 (t/h)	219.5	145.5	160.9	170.7	134.5	151.6	124.2	128.0	128.0	115.8	157.3	180.0
RFLD1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RFLD2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FTB1 (t/h)	240.0	240.0	200.0	200.0	220.9	225.2	207.7	201.1	220.1	225.2	191.7	200.0
FTB2 (t/h)	204.9	202.0	235.0	222.8	200.0	200.0	191.4	200.0	200.0	181.1	229.7	227.0
FTB3 (t/h)	240.0	240.0	240.0	238.1	240.0	228.6	240.0	240.0	217.6	238.4	230.3	238.9
FTLD1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FTLD2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RBB1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RBB2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RBLD1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P1 to AK (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	41.7	32.0	0.0	0.0	0.0	0.0
P1 to PPCA (t/h)	0.0	0.0	71.2	66.2	66.2	0.0	0.0	66.2	0.0	0.0	71.2	0.0
P2 to PPCA (t/h)	71.2	71.2	0.0	0.0	0.0	66.2	66.2	0.0	66.2	71.2	0.0	71.2
P3 to RF (t/h)	10.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P3 to FT (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P4 to AK (t/h)	0.0	0.0	0.0	81.8	78.4	78.7	0.0	68.7	0.0	73.2	76.8	0.0
P4 to PPCA (t/h)	130.0	66.8	130.0	0.0	0.0	0.0	130.0	61.3	79.8	56.8	53.2	53.4
P5 to AK (t/h)	90.2	86.7	86.1	0.0	0.0	0.0	65.7	0.0	117.9	0.0	0.0	81.3
P5 to PPCA (t/h)	29.8	33.3	33.9	92.0	81.9	120.0	53.8	120.0	2.1	120.0	120.0	38.7
P6 to PPCA (t/h)	50.3	110.0	38.1	110.0	110.0	67.9	0.0	10.6	110.0	20.2	28.8	110.0
P7 to RF (t/h)	130.0	130.0	130.0	90.3	86.7	86.7	46.0	46.0	46.0	126.0	130.0	130.0
P8 to RB (t/h)	155.0	155.0	155.0	153.1	142.9	132.7	121.4	121.4	127.6	137.8	148.0	155.0
P9 to PPCA (t/h)	72.7	0.0	72.7	0.0	54.5	0.0	54.5	0.0	54.5	0.0	72.7	72.7
P10 to PPCA (t/h)	0.0	72.7	0.0	54.5	0.0	54.5	0.0	54.5	0.0	72.7	0.0	0.0
P11 to RB (t/h)	23.6	18.5	18.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.3
CSPPT1 (MW)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	44.6
CSPPT2 (MW)	34.0	48.0	53.8	60.0	60.0	60.0	60.0	60.0	60.0	60.0	58.7	58.6
CSPPT3 (MW)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
CSPPT4 (MW)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
CSPPT5 (MW)	0.0	0.0	70.0	70.0	70.0	0.0	0.0	0.0	70.0	0.0	70.0	70.0
CSPPT6 (MW)	70.0	70.0	0.0	0.0	0.0	70.0	70.0	70.0	0.0	70.0	0.0	0.0
CSPPT7 (MW)	35.6	35.6	35.6	35.6	35.6	35.6	44.2	35.6	35.6	35.6	35.6	35.6
CSPPT8 (MW)	35.6	35.6	35.6	35.6	35.6	35.6	35.6	43.4	39.4	35.6	35.6	35.6
RFT1 (MW)	25.0	16.4	16.4	17.1	25.0	20.4	25.0	25.0	25.0	23.0	17.3	22.4
RFT2 (MW)	25.0	25.0	25.0	19.6	16.6	25.0	25.0	25.0	25.0	25.0	21.3	25.0
FTT1 (MW)	25.0	25.0	24.5	25.0	24.5	22.5	21.3	14.3	14.3	14.1	15.3	24.7
FTT2 (MW)	24.5	17.7	24.5	25.0	17.2	25.0	25.0	25.0	24.5	25.0	25.0	17.2
FTT3 (MW)	18.5	25.0	17.9	15.4	23.7	17.2	17.2	25.0	24.5	25.0	24.5	24.5
PowerBuyMax (MW)	43.3	30.7	30.0	29.5	30.4	30.1	45.6	46.4	45.9	29.9	30.0	39.2

cesses, as a large spare capacity indicates high optimization potential. The boiler operational schemes in SPPOSEF during T1–3 and T11–12 are analogous to one another because of the higher utility energy demand, which decreases the freedom of optimization.

As discussed in Ref. [33], the pipe connections provide great flexibility and redundancy of utility energy supply and backup from one SPP to another. The utilization of the advantage of inter-plant utility energy supply and backup to reduce the total cost is significant. However, it is impossible for the current SPPS to handle the equipment failure situations with a fixed pipe transportation load from a real period to a virtual period for RFSPP and FTSPP because of their small design redundancy. More boilers or more pipes from CSPP should be added. For comparison, more CSPPMP steam imported from CSPP to RFSPP or FTSPP is assumed, making it feasible for the SPPs to handle the equipment failure situations with fixed pipe transportation from real periods to virtual periods. Scheme SPPOSEFNP is presented in Table 8. The total annual cost is M¥ 5066.8, which is 2.62% higher than that of scheme SPPOSEF. Note that, although RFSPP and FTSPP are feasible under the maximum consumption of 260 t/h MP imported from CSPP with a fixed pipe load, the HP steam in RSPP or FTSPP becomes surplus or is decreased to a lower level at some period to reserve enough steam for virtual periods because of the limited SPP design load capacity, resulting in a large economic penalty. These results indicate that the FTSPP is not flexible enough to cope with emergency situations even with the aid of CSPP through pipe P3. Therefore, the retrofit is suggested for FTSPP. The recommended retrofit projects include constructing more boilers to increase steam generation capacity or pipe connections to import steam from other SPPs (e.g., CSPP).

Table8
Optimaloperation schemes (SPPOSEFNP) of boiler steam generation, turbine power generation, and pipe transportation in the planning horizon considering equipment failure with fixed pipe transportation load from normal conditions to equipment failure conditions.

Operation load	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
CSPPB1 (t/h)	246.0	246.0	264.2	248.4	246.0	246.0	246.0	0.0	246.0	246.0	246.0	246.0
CSPPB2 (t/h)	338.3	353.7	362.0	362.0	305.0	246.0	257.3	257.2	248.2	335.8	360.3	295.3
CSPPB3 (t/h)	410.0	410.0	410.0	410.0	410.0	0.0	410.0	410.0	410.0	410.0	410.0	410.0
CSPPB4 (t/h)	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0	410.0
CSPPB5 (t/h)	0.0	0.0	0.0	0.0	0.0	246.0	0.0	0.0	0.0	0.0	0.0	0.0
CSPPB6 (t/h)	0.0	0.0	0.0	0.0	0.0	246.0	0.0	246.0	0.0	0.0	0.0	0.0
CSPPB7 (t/h)	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0
CSPPB8 (t/h)	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0	364.0
AKB1 (t/h)	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0
AKB2 (t/h)	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0
AKB3 (t/h)	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0	104.0
AKLD1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AKLD2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RFB1 (t/h)	168.5	123.2	123.2	129.4	132.6	118.2	132.6	132.6	132.6	129.4	123.2	141.0
RFB2 (t/h)	168.5	123.2	123.2	129.4	132.6	118.2	132.6	132.6	132.6	129.4	123.2	141.0
RFLD1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RFLD2 (t/h)	83.8	5.8	5.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.8	13.5
FTB1 (t/h)	200.0	184.6	181.0	155.9	155.9	157.0	157.7	157.9	157.9	157.0	169.4	200.0
FTB2 (t/h)	200.0	184.6	181.0	155.9	155.9	157.0	157.7	157.9	157.9	157.0	169.4	200.0
FTB3 (t/h)	240.0	224.6	221.0	195.9	195.9	197.0	197.7	197.9	197.9	197.0	209.4	240.0
FTLD1 (t/h)	120.0	0.0	43.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	57.8
FTLD2(t/h)	0.0	66.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	94.0
RBB1 (t/h)	40.0	40.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.0
RBB2 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RBLD1 (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P1 to AK (t/h)	56.2	30.7	28.8	85.2	20.5	20.5	0.0	0.0	0.0	0.0	36.2	28.8
P1 to PPCA (t/h)	71.2	0.0	0.0	0.0	66.2	66.2	66.2	66.2	0.0	0.0	71.2	71.2
P2 to PPCA (t/h)	0.0	71.2	71.2	66.2	0.0	0.0	0.0	0.0	66.2	71.2	0.0	0.0
P3 to RF (t/h)	119.7	97.8	97.8	39.2	13.6	25.4	13.6	13.6	13.6	41.7	97.8	134.6
P3 to FT (t/h)	140.3	162.2	162.2	190.9	190.9	183.4	170.7	169.3	169.3	176.2	162.2	125.4
P4 to AK (t/h)	0.0	20.1	27.3	72.5	130.0	130.0	19.0	128.2	12.4	129.7	77.2	0.0
P4 to PPCA (t/h)	81.3	100.1	102.7	0.0	0.0	0.0	111.0	1.8	117.6	0.3	0.0	130.0
P5 to AK (t/h)	101.2	120.0	120.0	0.0	38.1	42.1	120.0	0.0	120.0	0.0	0.0	85.7
P5 to PPCA (t/h)	18.8	0.0	0.0	92.0	81.9	77.9	0.0	120.0	0.0	86.7	120.0	34.3
P6 to PPCA (t/h)	110.0	110.0	99.3	110.0	110.0	110.0	72.8	70.1	74.3	110.0	82.0	37.8
P7 to RF (t/h)	130.0	130.0	130.0	130.0	86.7	86.7	77.0	81.6	81.6	130.0	130.0	130.0
P8 to RB (t/h)	141.8	136.7	136.7	153.1	142.9	132.7	121.4	121.4	127.6	137.8	148.0	126.5
P9 to PPCA (t/h)	72.7	72.7	0.0	54.5	0.0	54.5	54.5	0.0	54.5	0.0	72.7	72.7
P10 to PPCA (t/h)	0.0	0.0	72.7	0.0	54.5	0.0	0.0	54.5	0.0	72.7	0.0	0.0
P11 to RB (t/h)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CSPPT1 (MW)	60.0	60.0	60.0	41.6	54.8	60.0	60.0	60.0	51.8	45.9	49.5	60.0
CSPPT2 (MW)	57.9	60.0	60.0	49.2	43.7	44.9	56.3	56.3	60.0	56.6	41.6	60.0
CSPPT3 (MW)	0.0	0.0	0.0	59.4	60.0	60.0	60.0	60.0	60.0	60.0	60.0	0.0
CSPPT4 (MW)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
CSPPT5 (MW)	0.0	70.0	70.0	0.0	70.0	70.0	0.0	0.0	70.0	70.0	70.0	0.0
CSPPT6 (MW)	70.0	0.0	0.0	70.0	0.0	0.0	70.0	70.0	0.0	0.0	0.0	70.0
CSPPT7 (MW)	49.9	49.9	55.1	35.6	35.6	40.5	35.6	36.4	35.6	40.2	41.6	50.1
CSPPT8 (MW)	47.2	50.1	49.9	42.6	39.2	35.6	36.4	35.6	35.9	35.6	35.6	49.9
RFT1 (MW)	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
RFT2 (MW)	25.0	25.0	25.0	25.0	25.0	20.4	25.0	25.0	25.0	25.0	25.0	25.0
FTT1 (MW)	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
FTT2 (MW)	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
FTT3 (MW)	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
PowerBuyMax (MW)	68.2	68.0	63.9	67.8	67.6	37.9	66.2	68.7	66.5	67.4	67.8	67.0

5.4. Scheme sensitivity to process buffer time

Process buffer time is a critical factor that determines both the redundancy capacity by increasing the operating boiler steam generation load and the power importation plan. Fig. 10 presents the total cost of varying trends with process buffer time, and Fig. 11 gives the relation of total cost with process buffer time. Enough redundancy is present even with zero min buffer time. Generally, power importation decreases directly with the increase in process buffer time during the whole planning horizon when the process buffer time is less than 5 min. The reason is that the SPPs reserve more operation load redundancy when the process buffer time is higher. Power importation increases slightly or remains constant when the process buffer time is greater than 5 min because the cost of a small amount of power importation is lower than that of reserving the corresponding operation redundancy. Fig. 11 shows that the total cost decreases with the increase in process buffer time because of the increasing load redundancy and decreasing power importation.

6. Conclusion

The current study presented a systematic methodology of the operational planning optimization considering equipment failure. The operating scenarios were classified into real period, which represents normal operation conditions, and virtual period, which indicates emergency conditions. The operation constraints were

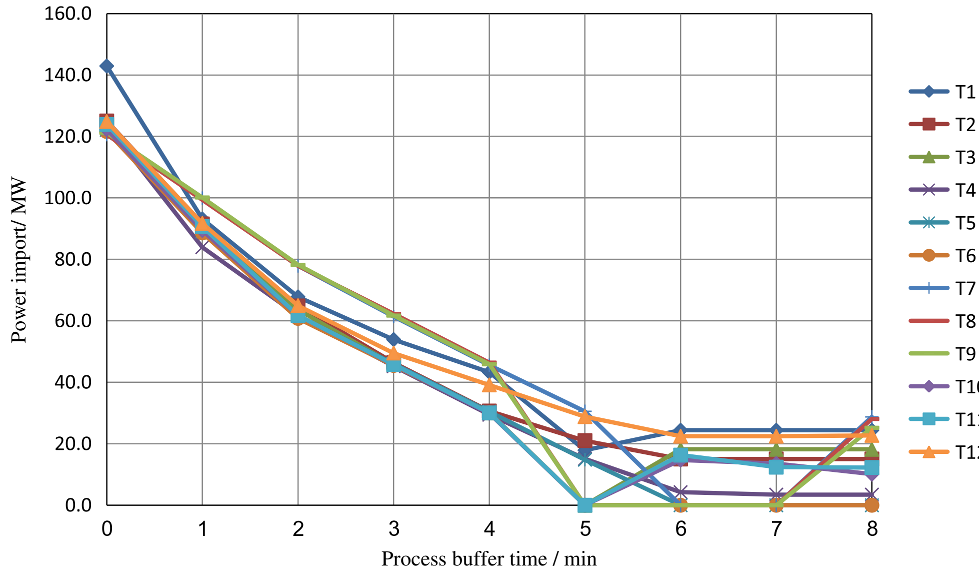

Fig. 10. The maximum power electricity importation versus process buffer time.

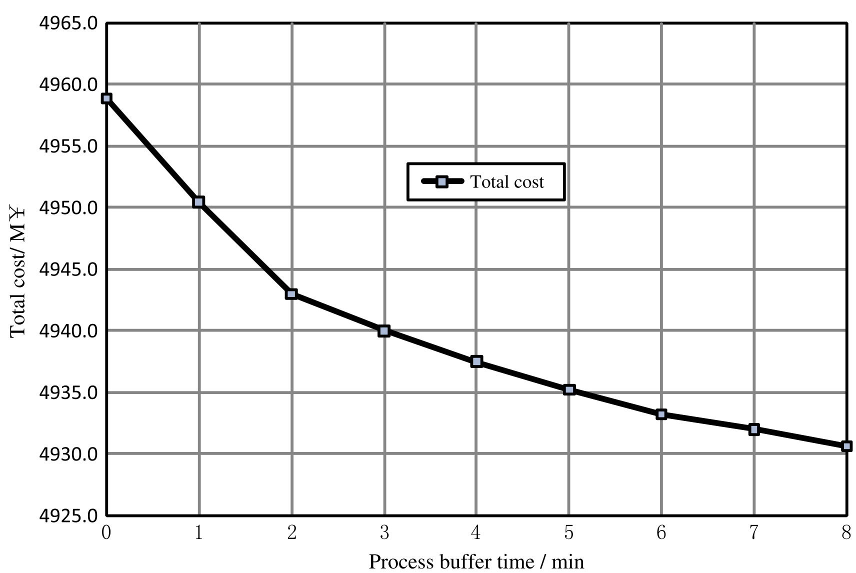

Fig. 11. The total cost versus process buffer time.

Table A.1
Coefficients of boiler model.

Boiler	*a*	*b*
CSPPB1	2901.8	−13175.0
CSPPB2	2883.2	−8981.9
CSPPB3, CSPPB4	2377.7	170002.7
CSPPB5, CSPPB6	2953.7	−25679.0
CSPPB7, CSPPB8	2693.1	38870.0
AKB1	2699.3	73965.0
AKB2, AKB3	2655.4	52917.0
RFB1, RFB2	2639.6	37018.0
FTB1, FTB2, FTB3	2742.8	23098.0
RBB1, RBB2	2957.0	13306.0

Table A.2
Power generation coefficients of turbine model.

Turbine	u	v_{MP}	v_{IP}	v_{LP}	v_{CP}
CSPPT1, CSPPT2	−12.1500	0.0911	0.2248	–	0.4305
CSPPT3, CSPPT4	−20.0200	–	0.2214	–	0.4631
CSPPT5, CSPPT6	−41.6980	–	–	0.3031	0.5815
CSPPT7, CSPPT8	18.3100	0.0795	0.1129	–	0.2474
AKDT1, AKDT2	0.2361	0.0617	–	–	0.2253
AKDT3, AKDT4	0.1528	–	0.1092	–	0.2253
RFT1, RFT2	−1.5861	0.0790	–	0.1529	0.3560
FTT1, FTT2, FTT3	−1.5861	0.0790	–	0.1529	0.3560

formulated under both real and virtual periods. A detailed MILP model was established to minimize the total cost for real period and reserve enough redundancy for the virtual period. A detailed industrial case study was presented to demonstrate the feasibility of the proposed method and MILP model. The following conclusions were drawn:

(1) The conventional optimal scheme SPPOSNEF of the studied case features cost minimization (i.e., M¥ 4916.6), but it cannot provide enough steam even without the power

Table A.3
Regenerative feed-water heating coefficients of turbine model.

Turbine	c	d_{MP}	d_{IP}	d_{LP}	d_{CP}
CSPPT1, CSPPT2	−19.4720	0.4217	0.5373	–	0.4604
CSPPT3, CSPPT4	5.0000	–	0.3514	–	0.3514
CSPPT5, CSPPT6	−94.0060	–	–	0.6442	0.8805
CSPPT7, CSPPT8	−14.5870	0.3938	0.5485	–	0.4480
RFT1, RFT2	−3.8819	0.3033	–	0.4108	0.3257
FTT1, FTT2, FTT3	−3.8819	0.3033	–	0.4108	0.3257

importation limitation for most of the virtual periods. The plant engineers' planned scheme SPPEPNEF based on the equal load allocation principle can provide higher flexibility than that of SPPOSNEF but not enough to some of the virtual periods even with a large total cost (i.e., M¥ 5276.4). Either of the two schemes can provide enough flexibility or guarantee operation safety.

(2) The classification of real and virtual periods is practicable and effective in representing normal operational conditions and emergency conditions. The formulated MILP model, which incorporates scenario classification, transition modeling, and equipment load increases modeling, power importation penalty, and equipment operation status controlling, making the cost minimization of normal operating condition possible while reserving enough flexibility and safety for emergency situations. The optimal scheme SPPOSEF, which reserves operation redundancy with relatively few additional cost penalties (i.e., total cost is M¥ 4937.5, which is 0.42% more than that of SPPOSNEF) is effective and provides safe operation schemes to cope with emergency situations.

(3) The equipment operation schemes are not only dependent on the equipment performance behavior in terms of economics and the environment but are also heavily dependent on the design redundancy (spare capacity) of the SPP where the equipment located. The pipe connections between SPPs provide great potential for the inter-plant supplying and inter-plant redundancy reserving. Utilizing the inter-plant redundancy effectively can guarantee not only enough flexibility but also cost reduction. The current SPPs are unable to deal with all the equipment failure situations without considering the pipe transportation load variation from the real period to the virtual period. Therefore, new equipment or new pipe connections are recommended to be added. The scheme SPPOSEFNP without considering the pipe transportation load variation from the real period to the virtual period is achieved under the assumption of having 115 t/h more MP steam imported from CSPP to RKSPP. The total cost is M¥ 5066.8, which is 2.62% higher than that of SPPOSEF.

(4) The proposed methodology is feasible and effective for operation optimization to meet multiple criteria, especially for large interconnected SPPs. As discussed in the case study, the proposed methodology is also helpful in providing system diagnosis and recommending reasonable retrofit projects. Therefore, the retrofit or design optimization for large and multiple interconnected SPPs considering equipment failure or other uncertainties (e.g., demand uncertainty and fuel price uncertainty) is a worthy research pursuit.

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Appendix A

Tables A.1–A.3

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